The Periodic Table and Genetic Code of the Hadrons

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A brief autobiographical summary is followed by a survey of the search for order in the Particle Spectrum, culminating in the discovery of the Octet model version of SU(3) symmetry. I then describe the research which led to the Quark concept, first as a mathematical model, then as a full-pledged physical model.

1. Introduction

This review, partly autobiographical, was presented at a special session held at Protvino Laboratory in June 2001, during the XXIVth International Workshop on Fundamental Problems of High-Energy Physics and Field Theory commemorating the "phase-transition" which occurred in the sixties in our thinking about the hadrons. This was the result of advances both in experimental techniques and in theoretical methodology, namely the 1960-63 discoveries : on the one hand, the great increase in the number of known states in the hadron spectrum, brought about by the discovery of *resonance* particles – and on the other hand, the understanding of the pattern presented by the hadronic spectrum, as provided by the *eightfold way* version of 577(3), then followed by the discovery of hadronic structure, as given by the *quark* model.

I would like to thank Professors A.A. Logunov and V. Petrov for their initiating this 40th anniversary celebration, rather than waiting for the more common "golden" 50^{th}) anniversary – with its somewhat strained longevity requirements. I would also like to greet Professor Bogdan Maglich, my experimentalist colleague of the sixties, co-speaker at the commemorative session and a friend of 40 years.

The events of 1961–63 [1–12] have been reviewed on several occasions. At the personal level, the most Comprehensive are the ones we presented [13, 14] at the 1983 *Symmetries in Physics 1600-1980,* an international meeting (originally intended to serve as the first in a series on the history of ideas) organized by the University of Barcelona at St Feliu de Guixols, with published proceedings, edited by M. Doncel et al. We have, Prof. Gell–Mann and I, most recently added our contributions at that meeting, to *The Eightfold Way* collection, in its 2001 republication by Perseus Press [15]. The competing alternative (non-exploratory) approaches were best covered in ref [16], the ideologies involved were discussed in refs. [17, 18, 19], the dependence of classification in Physics upon classification in Mathematics in ref. [20], connections with classical Greek ideas in [21].

2. The *Particle Century* 's first sixty (1897-1957) and my first thirty-five (1925-1960) years

In the title he chose for a collection of reviews he recently edited [11], Gordon Fraser dubbed the XXth century "The Particle Century" – a well-founded choice, considering that this century almost spans the entire list, from J.J. Thomson's discovery of the *electron* in 1897 and A. Einstein's 1905 demonstration of the particle nature *of the photon* in his study of the photoelectric effect — up to the 1994–95 discovery of the *top* (and presumably last) quark. Taking either my arrival in London in mid-December 1957 as Colonel Ne'eman, the Israeli Embassy's new Military, Naval and Air Attache, also similarly accredited to the Israeli Embassies at Copenhagen, Oslo, Stockholm and Helsinki – or, two weeks later, my knocking at the door of a Professor of Theoretical Physics named Brockman at *Imperial College of Science and Technology,* or perhaps even better, May 1st, 1960,

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when I resigned from the Attache positions and joined Imperial College as a full-time graduate student, with a one-year fellowship from the Israeli Government – taking either event as marking my entrance into physics, we can describe the encounter as happening roughly in the sixtieth year of the century and in my thirty-fifth – an encounter between two rather mature entities.

Going by age, we shall start with the Particle Century. By 1960 it listed two charged and either one or two neutral *leptons* (the existence of distinguishable *electronic* and *muonic* neutrinos – independently suggested by M. Gell-Mann and by N. Cabibbo – was soon to be proven experimentally). The *massless photon y* γ^0 was the only known *interaction-mediating boson.* For the *hadrons* (still named *strongly interacting particles* until 1962, when L. Okun suggested the term *hadron)* there were 7 spinless odd-parity mesons $(\pi^+, \pi^0, \pi^-; K^+, K^); \bar{K}^0, \bar{K}^-)$ and either 6 or 8 spin -parity $J^+ = 1/2^+$ baryons $(p^+, n^0; \Lambda^0; \Sigma^+, \Sigma^0, \Sigma^-; \Xi^0, \Xi^-)$, where the spin of the last two was as yet unconfirmed. Applying the *internal* quantum number introduced by Heisenberg around 1932, after Chadwick's discovery of the neutron, these states were grouped in *isomultiplets* with *isospin* I, a mathematical abstraction behaving like a (quantum) spin angular momentum, i.e. like the double-covering group of the group of rotations in three dimensions, (i.e. of unimodular orthogonal transformations in 3 real dimensions) $\overline{SO}(3) = SU(2)$, i.e.which coincides with unimodular unitary transformations in 2 complex dimensions, as had been realized by Pauli and by mathematicians such as Cartan and van der Waerden, with the discovery of spin; to complete the description and designation we add the *strangeness* S or better the hypercharge $Y = B + S$,where $B$is the *baryon number* and where the electric charge is given by the Gell-Mann - Nishijima rule $Q = I^3 + (1/2)Y$, namely for the lowest laying states,

$$J^p = 0^- : [\{pi, I = 1, Y = 0\}; \{K, I = 1/2, Y = 1\}; \{\bar{K} I = 1/2, Y = -1\}];$$

for the mesons; for the baryons,

$$J^p = (1/2)^+ : [\{N, I = 1/2, Y = 1\}; \{\Lambda I = 0, Y = 0\}; \{\Sigma I = 1, Y = 0\}];$$

with perhaps also (as the J^p was uncertain) $[\{\Xi I = 1/2, Y = -1\}]$.

In addition, since Fermi's experiments in the early fifties there were several sets of *resonant* states, such as the 4 Δ states with $J^p = (3/2)^+, I = 3/2, Y = 1$ all roughly at 1235 MeV and several other isomultiplets all in the (N, π) channel, with mounting half-integer spins J, alternating relative parities and either $I = 1/2$ or $I = 3/2$. Altogether, some 50 hadrons were listed - until the mid sixties, when they started multiplying rapidly as a result of experimental improvements, such as the introduction of the bubble-chamber, or of on-line software - topics that will be covered in Prof. Maglich's talk. The meson list, in particular, soon included (massive) vectorial $J^p = 1^{-1}$ and tensorial $J^p = 2^{+1}$ mesons-some of which had been predicted in the fifties by theorists interpreting observed effects. Thus, in 1956, E. Teller [22] had conjectured the existence of a massive (i.e. short-ranged) vector meson coupled to baryon number, as an explanation for the observed *hard core* resistance to compression in nuclei; T.D. Lee and C.N. Yang [23] had shown earlier that such a vector-meson could anyhow not be massless without interfering with gravity andwould thus have been detected in the Eotvos experiments. In 1957, Y. Nambu [24] had explained the unexpected profile of the nucleons' electromagnetic structure as observed in the Hofstadter experiments at Stanford by the existence of a vector-meson cloud surrounding the nucleon, relegating the pion cloud to a less fundamental role, a secondary entity, resulting from the decay of the first. Nambu's work, which was based on the experimental results for the isoscalar form factors, was generalized in 1960 by W. R. Frazer and J. R. Fulco [25] to the isovector channel as well. In 1960, J.J.J Sakurai [26] published a *"Vector Theory of the Strong Interactions",* postulating one more $1 = 0$ vector-meson, coupled to *hypercharge* 7, in addition to the above $I = 0$and $I = 1$ vector-mesons coupled to *baryon number* and *isospin.* The two isoscalar vector-mesons were inspired by the electromagnetic

4-potential (the photon) which also plays a role of *compensating field* in the preservation of *local gauge invariance,* as shown by H. Weyl [27] in 1929 for the U(l) *Abelian Lie Group* of the complex *phase* introduced by Schroedinger's wave function. C. N.Yang and R. Mills then constructed in 1953 the non-Abelian extension [28] which provided for a similar *Gauge Invariance* for any Lie Group, including here the case of isospin itself, yielding the $I = 1$ vector meson. Sakurai's VTSI [26] was based on a *local gauge-invariance* under the gauge group $SU(2)_I \otimes U(l)_Y \otimes U(1)_B$.

By the end of 1960, more than 100 different hadrons had been identified and the number was continuously increasing.

3. My first thirty-five years – and a historical diversion

I have given a brief autobiographical sketch in ref. [13] and shall only give an outline here, plus some more background.

I was born in 1925 in Tel-Aviv to a family with strong roots – three out of my four grandparents were born in Israel, in families who arrived around 1807-1811 (the country was a province of the Ottoman Turkish Empire throughout 1517-1918). The fourth, my paternal grandfather Abba Ne'eman was born in Lithuania (Alexod, the same village as Hermann Minkowski), was educated in German Koeningsberg (later Kaliningrad), immigrated to Israel in 1890 with an elder brother, and with their father Ary-Zeev Ne'eman following in their footsteps a few years later and settling in Jerusalem - also making arrangements to be buried on the Mount of Olives, next to his own grandfather Israel Ne'eman. The latter had immigrated around 1830 but fell from his camel while on his way from Jaffa to Jerusalem and died a few days later.

Abba was an engineer and an inventor and founded in 1900 a Pump factory which lasted until 1985. He was also one of the 66 founders of the city of Tel-Aviv (1909), with his wife - my grandmother Sarah, nee Mouchly, well-known for her care for the needy. She was the daughter of the clockmaker who built the town-clock on the tower in Jaffa and the sister of the Einsteins' (Albert and Else) host in Port-Said as described in Einstein's diary for 14-16 February 1923. My father was also an engineer and took over the pump factory when my grandfather retired, and I was supposed to do the same. I did graduate in 1945 as a mechanical engineer from the Haifa Technion, joined the factory and managed to design three models before being engulfed in military action.

I had matriculated at fifteen, then had to wait a year before being admitted by the Technion which had a minimal entrance age of 16. I spent that year (1940 $\sim$ 41) at the pump factory plus joining the Hagana, the Jewish underground army and was active in it throughout my 4 years at the Technion, including the Officer's Course which I took in 1945. At this point, I have to provide the reader with the background story so that my personal activities can be set in their context. I shall do my best to present it all objectively but I imagine it may still look subjective to some.

Very roughly, the background events *as seen from my angle* consisted in the Jewish people returning to their biblical fatherland, a stochastic motion of individuals throughout the ages, but now organized by the Zionist movement, since its founding in 1897 by Theodore Herzl. He was a Viennese journalist covering the Dreyfus trial in Paris, whose refined antennae, when faced with the antisemitic outburst in a nation and a capital city which were considered as the most liberal in Europe, sensed the coming of the Holocaust and the urgency of an Exodus from Europe. The Zionist movement and its aims were formally and internationally recognized, first by the British Balfour Declaration (1917) and later by the 1921 *League of Nations Mandate* to the U.K. <u>for Palestine</u> to <u>become</u> a <u>Jewish</u> *"Homeland"*[2].

[2] In the Roman Empire, the name of the (167 BC - 92 AD) Hasmonean-Herodian kingdom *of Judea,* which had (70 - 92 AD) become the province *of Judea,* was changed in 135 AD by Hadrian to *Palestine,* after his repression of the Bar-Kokhva rebellion, to weaken the link between the country and its people, whom he had exiled.

Around the same time, however, in encouraging the sharif Hussein I, Arab guardian of the Muslim holy shrines at Mecca and Medina, to rise against the Turks (the *saga* of Lawrence of Arabia) Britain also promised an independent state (or states?) to the Arabs, without specifying boundaries between the two commitments; the mood was optimistic, as witnessed by the 1919 friendly negotiations in Versailles, between Prince Feysal, son of Hussein I, and Prof. H. Weizmann, then President of the Zionist Organisation. Many on all three sides thought that there was a good case for a fruitful cooperation between the two newly established nationhoods, with the Jewish settlers bringing in modern skills and helping develop the Arab economies. To smoothen the mutual acceptance further, in 1920, Winston Churchill (then Colonial Secretary) enacted a *First Partition:* the Mandate having been granted over a territory covering roughly the entire area of Biblical Israel (or of the Judea of the Romans), 80% of the territory were now unilaterally excluded from the clauses relating to the Balfour Declaration and reconstituted as the Emirate of Transjordan, a new Arab state, thereby reducing the future "Jewish Homeland" to some 20% of the area first allotted.. And yet this did not avert the first outbreak of local Arab Resistance to the entire idea, onslaughts on the Jewish population, in the style of the massacres of the Christians in XIXth Century Lebanon, which lasted throughout 1920-21 and were renewed in 1929, and again in 1936-39. One result of this struggle was the gradual emergence of a now national entity, a crystallization of the Palestinian Arab body. The "global" clash between the underdog embryonic Jewish state and the Arab world was now extended by the development of a "local" confrontation the new Palestinian Arab entity could by the end of the XXth century attract liberal sympathies as the underdog. Meanwhile, the British, who had also founded the Arab League, thus found themselves caught between the two entities they had launched and courted – until in 1938 they gave in to local Arab action, supported by pressure on the part of the Arab League states – and cancelled the Balfour Declaration commitments altogether, in a *white paper.* It was now the Jews' turn to protest, and several underground movements were founded then. Throughout 1940–45, however, the Second World War was raging outside and the Jewish organizations refrained from action, choosing instead *to fight with the British against the Nazi arch-enemy.* With the end of the war in 1945, the clash with Britain reappeared immediately, when the UK refused to allow the renewal of Jewish immigration, rejecting even the recommendation on the part of an Anglo-American Public Commission to admit 100,000 Holocaust survivors found in the Concentration Camps ("DP"). 1946 thus became in Palestine the year of a military confrontation, with the Hagana organizing the DP's immigration, the Mandatory power's negative decision notwithstanding; another forced clash related to the continuation of Jewish settling on the land (once it was properly purchased) even though this too had been forbidden. Meanwhile, the United Nations passed a decision to partition Palestine into two states, an Arab and a Jewish one. The Jewish side accepted this *second partition,* the Arabs refused and attempted to destroy the Jewish cities and settlements which were the nucleus for the future State. The British decided to evacuate the country in May 1948 while it was being invaded by the armies of the Arab League.

The 1947–49 War (Israel's *War of Independence)* lasted 14 months and the cost in Israeli lives was enormous – one percent of the total Jewish population was killed in it Let me quote from Clement Attlee's (British Prime-Minister in 1945–1951) bookreview [29] (published in the *Observer)* of the Memoirs of Field Marshal Montgomery, who had been the CIGS - Chief of the Imperial General Staff in 1947–50. After praising Montgomery as a great soldier in the field, Attlee writes about his performance in 1947-48, "His judgment, too, seemed less good than it had been – he told me, for instance, that if there was a flare-up in the Middle-East, the Arabs would "hit the Jews for six" into the sea. We soon saw who did the hitting".

Judging by numbers and weaponry, Montgomery was right in his expectation of a rapid and complete Arab victory - the proportions between the overall strengths were something of the order of 10:1. The available weapons on our side were so limited that a batallion of 700 men would sometime carry about fifty rifles and some twenty lighter arms. Nevertheless, we won! This was due (1) to our having no alternatives and – had we had to face a defeat, it would be with our back to the sea, (2) supply of weapons of all sorts by the USSR (versus an American Embargo!) and (3) better leadership on our side, namely an active and unrestricted participation on the part of the intelligentsia. Example (other than myself) General Yigael Yadin — the leading Dead Sea Scrolls archeologist - also Chief of Operations in 47–49, later Chief of Staff. This involvement of the intelligentsia happens in cases in which a new nation is born, or a new system, a political phase-transition — Franklin and Jefferson in the American revolution (and Benjamin Thomson who fought on the other side), Lavoisier, Carnot, Fourier, etc. in the French Revolution.

Returning to my own story, I partook in everything which occurred from 1940 on, including field commands in 1948 and culminating as Director of Planning. I have described the civilian aspects which were involved in the latter activity in my evening lecture and contribution to the Vllth Marcel Grossmann Conference at Stanford, in 1994 [30]. This went on till late in 1957. After the 1956 Sinai-Suez campaign, tensions had diminished and I felt that this was the time to do what I had wanted to do since my Technion days - study Physics, provided I was not too old already.

My interest had originally been in Mathematics, but a series of lectures by Samboursky (who took his Ph.D. in Berlin under Theodore Kaluza) followed by reading Eddington and in my last year at the Technion, constituting a one-man class listening to Franz Ollendorf (the model of the Leslie Howard film Pimpernel Smith) solving the Schroedinger equation for the hydrogen atom - this converted me to Physics. I now (1957) asked for a two-years leave from the army to work at the Technion under N. Rosen, Einstein's collaborator in many important papers, who had just settled in Israel and founded a Physics Department at the Technion – but I ended up accepting the alternative suggested by my Chief of Staff, General Dayan, namely going to London as the Defense Attache and studying Physics at the same time. My idea of the frontier in Physics was centered on General Relativity, which I had taught myself. In London, I was planning to study under H. Bondi (of Steady State Theory) but I found this was impractical due to London traffic. Instead, I discovered Imperial College almost next door to the Embassy, talked to the Professor of Theoretical Physics listed in the catalogue, asking him who would be teaching Einstein's Unified Field Theory – which he answered "I don't know about UFT, but if you want to work in Field Theory, talk to Salam in the Old Huxley Building", which I did. Here we rejoin the story as I left it at the beginning of section 2.

The spring term of 1958 was not too crowded and I was catching up – when in July, a revolution occurred in Iraq and I was busy negotiating the purchase of two submarines (our first, in Israel) and fifty tanks and organizing the training of the crews. This was not my deal with Gen Dayan and I complained. As a result, I was able to resign from the Army and received a one-year fellowship.

4. The various approaches to the (1949–1962) search for order

We now return to Physics. From the 1949-50 discovery of the three components of the pion isomultiplet on, it became clear that one should try and bring some order into the system. The main lines followed can be arranged in the following categories, going from aproaches stemming from *some fundamental* assumption – to apparently *ad hoc* treaments:

A. The *Mechanistic* approach:

This was led by the group at the Institut Henri Poincare in Paris, headed by L. De Broglie – with a parallel group in Japan. The idea was in the spirit of Lord Kelvin's aether and other XlXth Century models, which postulated a mechanical origin for the whole of physics. The end-product was an article [31] signed by L. De Broglie, D. Bohm, P. Hillion, F. Halbwachs, T. Takabayasi and J.P. Vigier in *Phys. Rev.* The idea here was that isospin and any other internal degrees of freedom must arise from an internally spinning top (for an $SU(2)$), or other such internal mechanics (e.g. Feshbach suggested parastatistics for the $U(1)$ of strangeness) – where *internal* here stands for something mechanical, present in the interior of the particle. *Isospin* was assumed to represent the motion of the *internal spinning top.* The weakness in this approach was in its allowing spin and isospin to add up, as both are just angular momenta in this view. No such transition was ever observed.

B. The *Structuralist* approach:

This was based on guessing correctly at the simplest set of particles containing all ingredients (conserved Quantum Numbers) found in the hadron spectrum. The first such model was suggested after the discovery of the pions by E. Fermi and C.N. Yang [32], conjecturing that the pions are just nucleon-antinucleon compounds, namely $\pi^+ := \pi\bar{n}, \pi^0 := (2)^{-1/2}(p\bar{p} - n\bar{n}), \pi^- := n\bar{n}$. With the advent of strange particles, M. Goldhaber [33] added the kaon, while S. Sakata [34] added the Λ^0 and W. Thirring and L. Okun developed similar models. In 1959, Yukawa suggested using group theory to work out the complete spectrum of states resultin from the Sakata model and this was achieved by the Nagoya University group [35]. This model and the $SU(3)$ symmetry group it entailed were the most popular among particle physicists throughout 1958–1962. Note that in the presentation of the Sakata model by Sakata, Taketani and other members of this team (including the philosopher Fujimoto [18]), the emphasis was often on Marxist ideology in its Dialectical Materialist philosophical version [19]. In 1962, however, the model was found to clash with experimental results in nucleon-antinucleon annihilation into two mesons [36].

C. *Iso-rotational Sequential* Generalization.

The existence *of a global symmetry group G* implies (1) a *classification* of the states in the hadron Hilbert space in *unitary representations* of the group; (2) relations between couplings of particles within the same set of representations; (3) relations between matrix elements of operators whose behaviour under G is known (such as the *weak or electromagnetic currents,* or *the symmetry - breaking contribution to the mass).* Particle theorists, being familiar with the rotation group, assumed it was also nature's favorite. After the advent of strangeness (or hypercharge), A. Salam and J.C. Polkinghorne [37] enlarged the symmetry from isospin's $SO(3)$ to $SO(4)$; with three pions and four kaons, M. Gell-Mann [38] and J. Schwinger [39] proposed a model which, as was shown by J. Tiomno [40], postulated an $SO(7)$ symmetry; A. Salam and J.C. Ward then presented models based on $SO(8)$ and $SO(9)$ [41]. All of these models assumed that matter somehow had a preference for rotational symmetry.

D. *Comprehensive Assay* of all semi-simple Lie Algebras – an abstract identification of *the pattern*

This was the method I picked, when I embarked (in June 1960) on what Salam termed "a highly speculative search". He had wanted me to work on what we now know as the *Higgsmeson-triggered spontaneous symmetry breakdown* ", namely find out "how does a gauge vector-meson acquire mass?". After settling down at a desk at Imperial College in early May, I had been playing the game according to method C (I too knew only rotation groups), gradually rediscovering the various $SO(n)$ models, with $n = 3, 4, 7$, thereby aquiring confidence, as I was finding that I was not doing crazy things. Seeing that I was set on pursuing the "search for order" he then advised "if so, then go at it in depth, do not be satisfied with the little group theory I know and taught you!" He mentioned Dynkin, about whom he had just heard from Hamermesh, as somebody who had discovered some subgroups that even Racah ha d not known about. This was when I first heard about Racah's expertise in Group theory -1 knew Racah from my sitting in, as the Defense Ministry's representative on the Israel Atomic Energy Commission in 1953-55, but I was then at best an engineer. I ordered Dynkin's *articles in the American Mathematical Society Translations* (Salam had said *"Transactions"* and I wasted a week searching through that journal) and realized he was classifying the *subgroups* while I did not know the *groups* themselves. I finally discovered a heliographed copy of Dynkin's *thesis* at the British Museum and "absorbed" its content - reproducing with an elegant *diagrammatic* technique Cartan's 1894 classification of the *Simple Lie algebras.* Returning to Racah, I learned from him later that in 1951 he had lectured at Princeton on Cartan's classification of the simple Lie Algebras and issued a brochure. His audience had included Abraham Pais, Abdus Salam, Murray Gell-Mann etc. Unfortunately, they had either not followed or forgotten...

Our reliance on the algebraic toolkit derived from Emmy Noether's two theorems (for global and for local symmetries). I *was going to classify the hadrons by exploiting Car tan's classification of the algebras..* I saw that I had first to fix the algebra's *rank,* i.e. the number of simultaneously diagonizable abelian operators. I decided that what we had observed in hadronic interactions meant that we should be after a Lie group of rank $r = 2$ as everything allowed by the conservation of I^3, Y seemed indeed to occur. There were 5 candidates: $A(2), B(2), C(2), D(2)$ and $G(2)$. $B(2)$ was the algebra of $SO(5)$, $D(2)$ that of $SO(4)$; $C(2)$ generated the Symplectic group in 4 dimensions, which was homomorphic to $SO(5)$ - as could be seen directly from the Dynkin diagram. $G(2)$ was one of the five exceptionals; I had to reconstruct it from the Dynkin diagram to know what it could do – and it then turned out it was a six- ended Star-of- David!! Had I been a believer or a mystic, I would have regarded it as a heavenly intervention. Not being of that frame of mind, I checked the $G(2)$ predictions and saw that they did not fit observations.

$A(2)$, the generating algebra of $SU(3)$ fitted perfectly, provided the spin-parity of the Ξ^0, Ξ^- be $J^p = (1/2)^+$ and we then classify the 8 baryons with this value of J^P in the octet (adjoint) representation; I reconsidered the alternatives and concluded that this was it! When Salam returned in October from his summer activities and the Rochester Conference, I presented him with a paper describing this model. It lay on his desk for a while – he was considering adding a section about the other model involving $SU(3)$, namely Sakata's. In my paper, I had included an assumption of $SU(3)$ as a local Yang-Mills gauge theory, which would contain Sakurai's VTSI plus 4 additional vector-mesons with the isospin- hypercharge assignments of the kaons. Salam now explained that this same Lie group had just been presented at Rochester by Ohnuki of the Nagoya team, and Salam intended to suggest that model too might be a *local* gauge symmetry, with the canonical set of vector particles. This set had to behave like the algebra, i,e, it had to be in the *adjoint* representation - independently of the identification of the representation of the baryons, so that we would have the same octet of vector- mesons for both the octet or the triplet baryons. The Nagoya group had selected as algebraic basis a set of matrices with $(1 - i)$ and $(1 + i)$ as elements, rather inconvenient — mine were like Pauli sigmas in the three $2x2$ submatrices of the defining $3x3$. However, I was new and naive and felt forced to use the Nagoya set because they had already been presented. I took off my jacket and went to work, messing up my matrices and making a new draft for Salam, with that basis. Salam appeared to have forgotten, and in January I enquired. He said he had changed his mind, he would publish the point about the same gauge-mesons fitting the two nodels elsewhere, and I could publish my work on my own. I sent my article (typed by my former secretary at the embassy) to Nuclear Physics ("received 13 February").

Murray Gell-Mann had also arrived at the same conclusion independently [2], a few weeks later, according to the detailed check conducted by his recent biographer, George Johnson [42]. Gell-Mann' s preprint arrived a few days after I had sent out my paper to the journal. We communicated and after two issues of the preprint, it was submitted to *Phys. Rev.* (received 27 March 1961). Later on, Gell-Mann also published his own comprehensive assay of the Cartan list, done with S. Glashow [43], justifying the octet choice for the baryons.

This, however also meant that the proton or neutron very probably should no more be regarded as elementary. When, within the next year, similar assays were performed by several groups (D.R. Speiser and J. Tarski [44]) or R.E. Behrends and A. Sirlin [45] - or when Y. Yamaguchi, one of the leading proponents of the Sakata model, noticed the possibility of an octet assignment for the baryons, they were frightened away by this fact - how could the nucleon not be elementary.

5. The baryon-octet version of $SU(3)$: verifying the "Eightfold Way" and applying it

The symmetry having been presumably identified, applications followed in the hundreds.

First — there was the issue *of fixing the behaiour* of various *physical operators:*

(a) The symmetry-breaking responsible for the unequal masses within a multiplet. We had noted that this appeared to be in the 8^{th} direction. Gell-Mann had calculated a mass-formula for octets and S. Okubo had worked out a general formula [46]. There appeared to be a paradox in the existence of a broken symmetry for a strong interaction [47] which I resolved later [48] by concluding that the strong interaction itself fully obeyed the symmetry - and the breaking derives from a non-strong high-energy interaction.

(b) The electromagnetic and weak currents - this led to a huge industry and to current algebra as a methodology [49].

Secondly — the classification as such, for the Hilbert Space states; with missing states in some multiplets — most obvious among the missing being the 8th component of the pseudo-scalars $J^p = 0^-$. Using the mass formula one could have the precise prediction for the missing state - and it was soon found and fitted the prediction. The most spectacular such prediction was that of the Ω semi-stable hyperon with $J^\mu = 3/2^+$ [51,52].

Thirdly — for a local gauge, one had to find a combined multiplet $8(+)1$ with $J^p = 1^{-1}$. It was found, though massive. It was then shown that this local gauge could be induced by electromagnetism, assuming that the matrix elements of the electromagnetic current are dominated in a dispersion relation by a pole corresponding to the hadronic vector-mesons. *Universality* of the couplings would be *effective* rather *than fundamental* - but this would only affect the interpretation [53].

Fourthly — one could now derive hundreds of intensity-rules, namely prdictions with respect to ratios between processes linked by the group [54].

Publication of the results of the Omega-minus experiment (February 1964) settled all doubts and $SU(3)$ in the baryon-octet version acquired a paradigmal status by concensus. This was then the "Periodic Chart" of the hadrons, very similar in its role to Dmitri Mendeleev's Periodic Chart of the chemical elements (there too, universal acceptance followed the discovery of elements predicted by the Chart). The next stage would have to be the discovery of the *structure* behind that ordering. In Mendeleev's case, it had to wait for Rutherford, Bohr and Pauli.

6. Finally, the structure (triplets — quarks)

In the late spring of 1961 there was a moment of doubt, caused by a wrong experimental result which spread as a rumor, even though it was not confirmed by other tests. The news was that the $\Sigma - \Lambda$ relative parity was odd. This clashed with the octet-version of $SU(3)$ and Gell-Mann withdrew his $SU(3)$ paper, resubmitting it later in a different presentation – with two different models presented together – the Sakata and ours. By September 1961 it was clear that the rumour had been a red herring.

Shortly afterwards, I started thinking about possible constituents of the hadrons. I noticed that we could "make" a baryon with 3 triplets, except that these would have *fractional* charges. With Haim Goldberg I worked out a model in which we indeed give $B = 1/3$ to the triplets [4]. Our paper was mathematical in its presentation. Almost two years later, the structure with 3 triplets, was given a formal *physical* presentation by Gell-Mann [7] and by G. Zweig [8]. The quark *model* grew with the advent of $SU(6)$ and other spin-unitary-spin combinations. The experiments at SLAC in 1968-70 established the model and in 1990, Jerome Friedman, Jim Kendall and R. Taylor were awarded with the Nobel Prize for having explored these models and established the presence of the quarks inside the nucleons. By 1975, the picture was complete - we had an understanding of the structure in terms of (apparently 3 "generations" of 2 "flavors" each and in 3 "colors") a total of 18 different quarks,providing the "genetic code" fixing the hadrons' properties.

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